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Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: Implications for classification and petrogenesis of A-type granites

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Abstract

The varying geochemical and petrogenetic nature of A-type granites is a controversial issue. The oxidized, magnetite-series A-type granites, defined by Anderson and Bender [Anderson, J.L., Bender, E.E., 1989. Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America. Lithos 23, 19–52.], are the most problematic as they do not strictly follow the original definition of A-type granites, and approach calc-alkaline and I-type granites in some aspects. The oxidized Jamon suite A-type granites of the Carajás province of the Amazonian craton are compared with the magnetite-series granites of Laurentia, and other representative A-type granites, including Finnish rapakivi and Lachlan Fold Belt A-type granites, as well as with calc-alkaline, I-type orogenic granites. The geochemistry and petrogenesis of different groups of A-types granites are discussed with an emphasis on oxidized A-type granites in order to define their geochemical signatures and to clarify the processes involved in their petrogenesis. Oxidized A-type granites are clearly distinguished from calc-alkaline Cordilleran granites not only regarding trace element composition, as previously demonstrated, but also in their major element geochemistry. Oxidized A-type granites have high whole-rock $FeO_t/(FeO_t+MgO)$, TiO_2/MgO, and K_2O/Na_2O and low Al_2O_3 and CaO compared to calc-alkaline granites. The contrast of Al_2O_3 contents in these two granite groups is remarkable. The $CaO/(FeO_t+MgO+TiO_2)$ vs. $CaO+Al_2O_3$ and $CaO/(FeO_t+MgO+TiO_2)$ vs. Al_2O_3 diagrams are proposed to distinguish A-type and calc-alkaline granites. Whole-rock $FeO_t/(FeO_t+MgO)$ and the $FeO_t/(FeO_t+MgO)$ vs. Al_2O_3 and $FeO_t/(FeO_t+MgO)$ vs. $Al_2O_3/(K_2O/Na_2O)$ diagrams are suggested for discrimination of oxidized and reduced A-type granites. Experimental data indicate that, besides pressure, the nature of A-type granites is dependent of fO_2 conditions and the water content of magma sources. Oxidized A-type magmas are considered to be derived from melts with appreciable water contents (≥ 4 wt.%), originating from lower crustal quartz-feldspathic igneous sources under oxidizing conditions, and which had clinopyroxene as an important residual phase. Reduced A-type granites may be derived from quartz-feldspathic igneous sources with a metasedimentary component or, alternatively, from differentiated tholeiitic sources. The imprint of the different magma sources is largely responsible for the geochemical and petrological contrasts between distinct A-type granite groups. Assuming conditions near the NNO buffer as a minimum for oxidized granites, magnetite-bearing granites formed near FMQ buffer conditions are not *stricto sensu* oxidized granites and a correspondence between oxidized and reduced A-type granites and, respectively, magnetite-series and ilmenite-series granites is not always observed.
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Keywords: Carajás; Amazonian craton; Oxidized granites; Reduced granites; Magnetite-series; Ilmenite-series; Rapakivi; A-type granite

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1. Introduction

A-type granites were defined as relatively anhydrous, reduced, anorogenic granites enriched in incompatible elements (Loiselle and Wones, 1979). Later, more detailed petrographic and geochemical criteria as well as petrogenetic models have been presented for A-type granites (Collins et al., 1982; Whalen et al., 1987; Eby, 1990, 1992; Whalen et al., 1996; Frost and Frost, 1997; Frost et al., 1999) and their exclusively anorogenic geotectonic setting has been questioned (e.g., Whalen et al., 1987; Sylvester, 1989; Whalen et al., 1996). Rapakivi granites were redefined by Haapala and Rämö (1992) as A-type granites characterized by the presence of rapakivi texture. The Mesoproterozoic A-type granites of the Laurentia–Baltica have been divided into three groups: ilmenite granites, magnetite granites and two-mica (peraluminous) granites (Anderson and Bender, 1989; Anderson and Morrison, 1992; Anderson and Smith, 1995; Anderson and Morrison, 2005). Most of the granite members of the anorthosite–mangerite–charnockite–rapakivi granite series (AMCG series; Emslie, 1991) belong to the ilmenite-series granites. Until recently, little attention has been given to the magnetite-series A-type granites. These are commonly seen with suspicion, because they do not follow strictly the original definition of A-type granites, and approach calc-alkaline and I-type granites in some aspects, e.g., in their oxidizing character.

Many authors have stressed the varying petrogenetic nature of A-type granites (Sylvester, 1989; Creaser et al., 1991; Eby, 1992; Hogan et al., 1992; Poitrasson et al., 1994; King et al., 1997; Patiño Douce, 1999; Rajesh, 2000; Dall'Agnol et al., 2005). Geochemical contrasts between typical peralkaline and metaluminous to mildly peraluminous A-type granites have also been emphasized (King et al., 1997; Patiño Douce, 1999; Costi, 2000). There is increasing evidence that the variations shown by A-type granites dominantly reflect contrasts in magma sources and petrological processes and are, thus, extremely relevant for the understanding of their petrogenesis. On the other hand, the relevance of oxidized A-type granites and their differences compared to ilmenite-series rapakivi granites were demonstrated in central and southwestern United States (Anderson and Bender, 1989; Anderson and Smith, 1995; Barnes et al., 2002; Anderson and Morrison, 2005) and eastern Amazonian craton (Dall'Agnol et al., 1997a, 1999a,b,c, Rämö et al., 2002; Dall'Agnol et al., 2005). Occurrences of oxidized, magnetite-series A-type granites have also been described in other continents (Rajesh, 2000; Bogaerts et al., 2003). Several chemical and petrogenetic classifications for granites have been proposed (see summaries by Barbarin, 1999; Frost et al., 2001). However, it should be evaluated how suitable they are for the discrimination of different A-type granite groups.

Experimental studies direct or indirectly concerning A-type magmas have been carried out (Clemens et al., 1986; Skjerlie and Johnston, 1993; Patiño Douce and Beard, 1995; Patiño Douce, 1997; Dall'Agnol et al., 1999c; Scaillet and Macdonald, 2001, 2003; Klimm et al., 2003). These studies established constraints for the origin and evolution of different A-type granite groups.

The aim of this paper is to present the geochemical and petrogenetic characteristics that can be used to distinguish between the oxidized, magnetite-series A-type granites from both other A-type granite groups, and calc-alkaline granitoid series. To do this, the A-type granites of the Carajás province of the Amazonian craton, Brazil, will be compared with representative A-type granites, including those of Laurentia–Baltica and Lachlan Fold Belt provinces, as well as with calc-alkaline, I-type orogenic granite series. In addition, major element geochemical diagrams for A-type granite classification and discrimination will be evaluated. The petrogenesis of oxidized A-type granites will be discussed taking into account constraints established by experimental petrology. This will be done in order to define the geochemical signature of oxidized A-type granites and to clarify the processes involved in their petrogenesis.

2. A-type granites of the Carajás province

A synthesis of the geological, tectonic, mineralogical, geochemical, isotopic, and petrogenetic aspects of the Paleoproterozoic A-type granites of the Carajás province of the eastern Amazonian craton and a brief comparison between them and the Mesoproterozoic A-type granites of Fennoscandia and Laurentia was presented by Dall'Agnol et al. (2005). More detailed information on the A-type granites of Carajás can be found in that paper and references therein. The aspects more relevant to the present paper will be reviewed in the following.

2.1. Geologic setting, geochronology and Nd isotope geochemistry

The Archean Carajás province of the Amazonian craton (Machado et al., 1991; Macambira and Lafon, 1995; Dall'Agnol et al., 1997b; Rämö et al., 2002) is divided into the Rio Maria Granite–Greenstone Terrane (3.0 to 2.86 Ga), and the rift-related Carajás Basin (2.76 to 2.55 Ga), located, respectively, in the southern and northern parts of the province. The Jamon, Serra dos Carajás, and Velho Guilherme Paleoproterozoic A-type,

rapakivi granite suites were recognized in the province (Fig. 1). These three suites differ in the degree of oxidation of their magmas and region of occurrence (see Dall'Agnol et al., 2005, and references therein). The oxidized granite plutons of the Jamon suite are found in the Rio Maria Granite–Greenstone Terrane (Dall'Agnol et al., 1997a; Althoff et al., 2000; Souza et al., 2001; Rämö et al., 2002; Dall'Agnol et al., 2005). The moderately reduced Serra dos Carajás suite plutons are exposed in the Carajás Basin (Dall'Agnol et al., 1994, 2005). The tin-mineralized, reduced Velho Guilherme suite plutons are located in the Xingu region, to the west of the province (Dall'Agnol et al., 1993; Teixeira et al., 2002). The A-type granite plutons of the Carajás province were formed at ~1.88 Ga (Machado et al., 1991; Macambira and Lafon, 1995; Dall'Agnol et al., 1999a,b; Teixeira et al., 2002; Dall'Agnol et al., 2005), and were emplaced in an extensional tectonic regime, as indicated by dike swarms that are coeval with the granites (Dall'Agnol et al., 2005). Lamarão et al. (2002, 2005) and Dall'Agnol et al. (2005) postulated that the A-type granite magmatism of the Carajás province was related to a continental event that marks the beginning of the breakup of the Paleoproterozoic continent formed at the end of the Trans-Amazonian orogenic cycle.

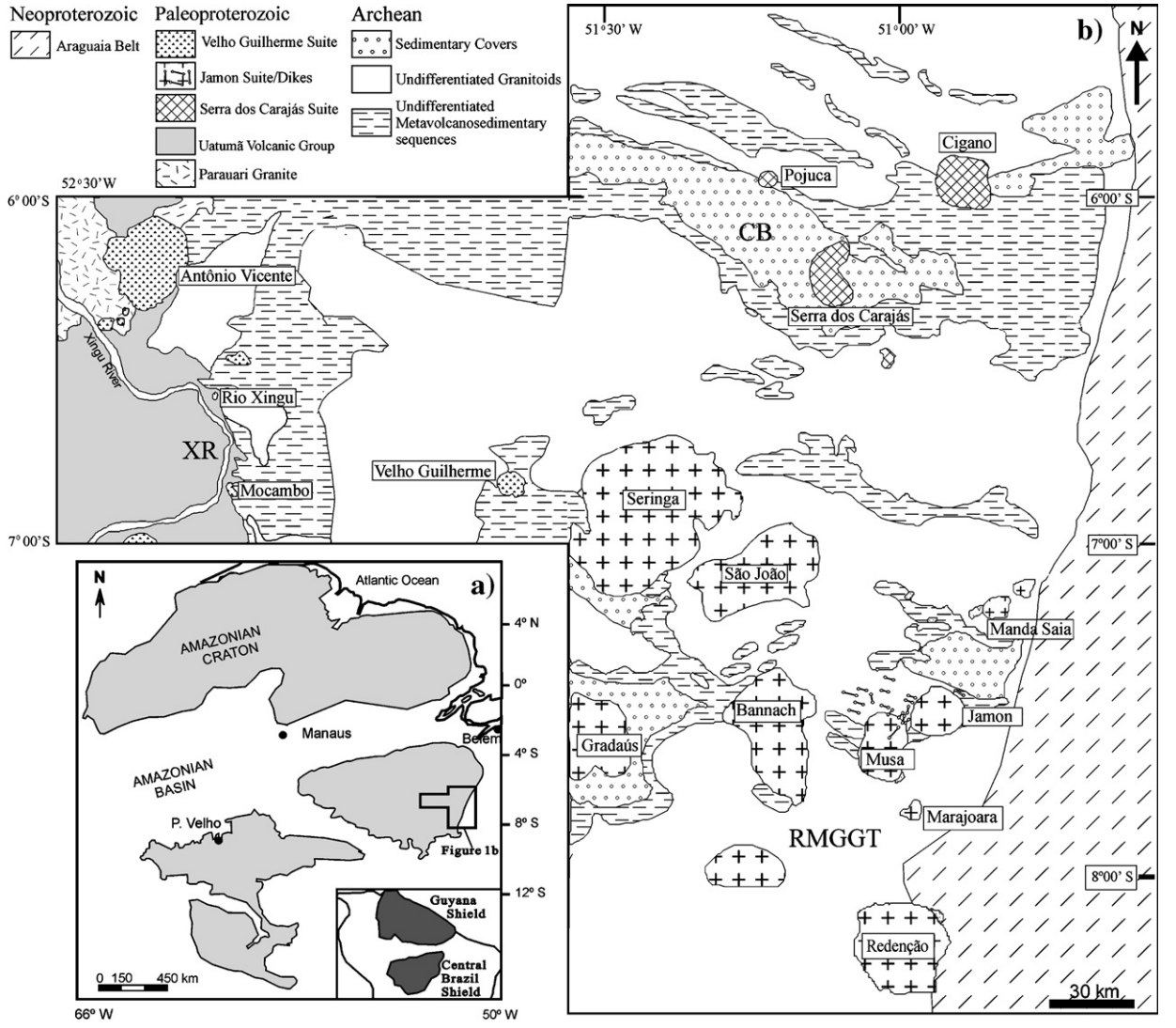


Fig. 1. (a) Location of the studied area in the Amazonian craton. (b) Simplified geological map of the Carajás Mining Province showing the distribution of Paleoproterozoic A-type granites (modified from Dall'Agnol et al., 2005, and references therein). RMGGT–Rio Maria Granite–Greenstone Terrane; CB–Carajas Basin; XR–Xingu Region. Inset in (a) shows the two exposed parts of the Amazonian craton–the Guiana shield in the north and the Central Brazil shield in the south.

Table 1
Modal compositions of the Paleoproterozoic A-type granites of the Jamon Suite

	Jamon (1)				Redenção (2)					Musa (3)				Bannach (4)					
	HBMzG [13]	BMzG [9]	BMcG [4]	LMzG [1]	CBAMzG [4]	BHMzG [6]	HBMzG [10]	BMzG [10]	BMzP [8]	LMzG [10]	BHMzG [3]	HBMzG [15]	BMzG [11]	LMzG [9]	LSG [5]	CBHMzG [3]	BHMzG [11]	HBMzG [9]	BMzP [4]	LMzG [14]
Plagioclase	30.2	28.6	35.9	30.1	33.0	33.0	29.3	29.0	27.8	24.7	30.9	31.1	28.0	26.0	18.2	26.4	34.5	33.6	26.1	25.7
Alkali-feldspar	29.4	33.4	35.1	32.5	20.3	25.9	30.5	33.7	34.0	39.0	27.6	31.5	33.4	37.5	46.6	17.8	24.2	28.7	30.1	34.6
Quartz	31.9	31.0	32.0	30.1	21.5	25.8	29.2	30.4	31.8	33.6	31.0	29.5	31.3	33.8	33.2	26.0	29.0	30.4	36.6	35.1
Clinopyroxene	<0.1	–	–	–	1.4	–	–	–	–	–	–	–	–	–	–	0.9	0.4	–	–	–
Amphibole	1.7	0.1	–	<0.1	11.2	6.2	2.5	0.3	0.3	–	4.0	1.7	0.3	–	–	16.4	5.3	1.4	–	–
Biotite	4.6	4.5	0.9	0.2	7.9	5.9	5.6	4.4	3.0	1.0	3.2	3.8	5.2	0.4	0.3	7.5	2.7	3.8	2.9	1.8
Chlorite	0.3	0.5	1.5	0.1	–	0.1	0.2	0.4	1.3	0.4	0.1	0.3	0.4	1.2	1.0	0.1	0.3	0.3	1.5	1.1
Opaques	0.8	0.8	0.6	0.7	3.5	2.1	1.8	1.1	0.8	0.6	1.7	0.8	0.6	0.5	0.4	3.8	1.9	0.7	1.4	–
Titanite	0.5	0.3	0.1	0.4	1.1	0.8	0.8	0.8	0.4	<0.1	0.6	0.8	0.5	0.3	1.0	0.4	0.1	0.2	0.6	–
Allanite	n.d.	n.d.	n.d.	n.d.	0.1	–	<0.1	0.1	0.3	–	0.1	0.1	0.1	0.1	<0.1	0.2	0.2	0.3	0.2	–
Fluorite	n.d.	n.d.	n.d.	n.d.	–	–	–	–	–	<0.1	<0.1	<0.1	<0.1	0.1	0.1	–	0.2	–	0.1	0.1
Others$^{(Ap+Zr)}$	0.4	0.5	0.5	0.2	0.2	0.1	0.1	<0.1	0.1	0.1	0.2	0.1	0.3	0.2	0.1	0.5	0.1	0.1	<0.1	–
Felsic	91.5	93.0	96.4	98.5	74.8	84.7	89.1	93.0	93.6	97.3	89.6	92.1	92.7	97.2	98.0	70.2	88.7	93.1	93.3	96.4
Mafic	8.4	6.9	3.6	1.5	25.5	15.1	11.1	6.9	6.2	2.6	10.4	7.7	7.3	2.8	2.0	29.8	11.3	6.9	6.7	3.6

(1) Dall'Agnol et al. (1994); (2) Oliveira (2001); (3) Gastal (1987) and Oliveira D.C. (unpubl. data); (4) Almeida et al., submitted for publication; [ ] number of averaged samples; n.d. = not determined; Ap = apatite; Zr = zircon; C = clinopyroxene; H = hornblende; B = biotite; MzG = monzogranite; McG = microgranite; SG = syenogranite; P = porphyritic; L = leuco.

Whole-rock Nd isotope data for the Jamon (Dall'Agnol et al., 1999b; Rämö et al., 2002), Velho Guilherme (Teixeira et al., 2002), and Serra dos Carajás (Dall'Agnol et al., 2005) suites imply remarkably similar ε_{Nd} (at 1880 Ma) values, ranging generally from −10.5 to −7.9. Data for the Jamon suite (Rämö et al., 2002) also indicate that the plutons were not disturbed and have retained their initial magmatic Nd isotope composition. The Nd isotope composition of the Archean country-rock granitoids complies with the idea that the Paleoproterozoic A-type Carajás granites were derived from deeper parts of the Archean crust (Dall'Agnol et al., 1999b; Rämö et al., 2002; Teixeira et al., 2002; Dall'Agnol et al., 2005).

2.2. Petrography and mineral chemistry

All three suites are composed essentially of granites *sensu stricto* (monzogranite to syenogranite with rare alkali feldspar granite; Dall'Agnol et al., 2005; modal compositions of the oxidized Jamon Suite granites are given on Table 1), with biotite or, in the less evolved facies, biotite and hornblende as the major mafic phases. Locally relict clinopyroxene crystals are associated with amphibole. Muscovite is present only in evolved, hydrothermally altered leucogranites. Isotropic, equigranular, coarse- or medium-grained and seriated rocks are dominant in most of the plutons. However, plagioclase mantled K-feldspar megacrysts are observed in every pluton and are quite common in some of them (e.g., Redenção, Bannach, and Serra dos Carajás). Nevertheless, the texture of the porphyritic facies of these plutons differs from typical wiborgitic rapakivi textures (cf. Rämö and Haapala, 1995) by the fact that tabular megacrysts are as common as ovoid megacrysts and that mantled K-feldspar megacrysts are subordinate relative to those unmantled by plagioclase.

The Fe/(Fe+Mg) in amphibole (0.47 to 0.73) and biotite (0.6 to 0.70), Fe–Ti oxide mineral data, and experimental studies (Dall'Agnol et al., 1997a, 1999c, 2005) demonstrate that the Jamon and associated felsic dike magmas evolved in relatively oxidizing conditions, above the NNO buffer. This is consistent with the presence of significant modal magnetite and titanite in all the facies of this suite.

In the Antonio Vicente complex of the Velho Guilherme suite (Teixeira, 1999; Dall'Agnol et al., 2005), the amphibole and biotite of the less evolved monzogranites have Fe/(Fe+Mg) between 0.74 and 0.85. In the alkali–feldspar granite, Fe/(Fe+Mg) in the amphibole and associated biotite are higher (0.95–0.98) than in the monzogranites. The biotite of the syenogranite has Fe/(Fe+Mg) of 0.85–0.89 and in the more evolved leucogranites of this suite, the mica is a siderophyllite with a Fe/(Fe+Mg) higher than 0.9. Except in the amphibole-bearing

monzogranite, where magnetite is found associated with ilmenite and titanite, magnetite and titanite are absent or very scarce. These data indicate that the dominant facies of the Velho Guilherme suite evolved under reducing conditions (Dall'Agnol et al., 2005). The amphibole-bearing monzogranite evolved in moderately reducing conditions, probably similar to those prevalent in the Serra dos Carajás suite (see below).

In the Cigano pluton, representative of the Serra dos Carajás suite, amphibole and biotite have, respectively, Fe/(Fe+Mg) in the range 0.85–0.94 and 0.78–0.88. The dominant Fe–Ti oxide mineral is magnetite, demonstrating that these granites crystallized at fO_2 above the FMQ buffer. However, their high whole-rock, amphibole, and biotite Fe/(Fe+Mg) ratios are compatible with those of reduced granites. This was interpreted to imply oxygen fugacity just a little above the FMQ buffer (Dall'Agnol et al., 2005).

2.3. Elemental geochemistry

Representative chemical compositions of the major facies of some Jamon Suite plutons are given in Table 2. Previous works (Dall'Agnol et al., 1993, 1994; Barros et al., 1995; Dall'Agnol et al., 1999b; Dall'Agnol et al., 2005) have shown that granites from the three Carajás suites plot in the A-type field in the geochemical classification of Whalen et al. (1987) and in the within-plate field of Pearce et al. (1984). They also show geochemical affinity with Finnish rapakivi granites (Figs. 2, 3; see Dall'Agnol et al., 1999a). Compared to the oxidized Jamon suite granites, the reduced and moderately reduced granites of the Velho Guilherme and Serra dos Carajás suites show a geochemical signature more similar to that of the A-type rapakivi granites. These have higher $FeO_t/(FeO_t+MgO)$, K_2O/Na_2O (Fig. 2d,e), and HFSE contents than the Jamon Suite granites. The granites have silica content >65 wt.%, generally >70 wt.%, and are metaluminous to mildly peraluminous, ferroan granites according to the terminology of Frost et al. (2001; see Fig. 2c,d).

2.4. Magnetic susceptibility and Fe–Ti oxides

Magnetic susceptibility (MS) decreases from the oxidized Jamon suite (1.05×10^{-3} to 54.73×10^{-3}, most values $>5.0\times10^{-3}$; MS in International System volume units) to the moderately reduced Serra dos Carajás suite (1.0×10^{-3} to 5.0×10^{-3}); the lowest values are found in the syenogranites of the Velho Guilherme suite ($<1.0\times10^{-3}$). The Jamon suite granites are typical magnetite-series according to the terminology of Ishihara (1981) with modal contents of Fe–Ti oxide minerals generally between 0.5 and 2% and magnetite dominant over ilmenite. Compared to Jamon, the Serra dos Carajás suite granites and the amphibole-bearing monzogranite of the Antonio Vicente complex (Velho Guilherme suite) have lower contents (<1%) of magnetite and ilmenite. It is important to realize that the moderately reduced Serra dos Carajás granites and the amphibole-bearing monzogranite of the Velho Guilherme suite have more than 0.1% modal magnetite and thus belong to the magnetite-series (Ishihara, 1981). The Velho Guilherme suite syenogranites, with opaque mineral contents generally <0.1%, and magnetite absent in most of the studied samples, classify as ilmenite-series.

3. Comparison with the Proterozoic A-type granites of Fennoscandia and Laurentia

The country rocks and probably also the sources of the Paleoproterozoic, A-type granites of Carajás region are all Archean and the three studied granite suites are practically coeval (~1.88 Ga; Dall'Agnol et al., 2005). In contrast, in Fennoscandia and Laurentia the granite magma sources, with the exception of the Salmi batholith (Rämö and Haapala, 1995; Amelin et al., 1997), are essentially Paleoproterozoic to Mesoproterozoic and the ages of the granites show significant variation (~1.7 to 1.1 Ga). The three Carajás suites evolved in varying fO_2 conditions, but do not exactly correspond to the three main granite groups identified in Laurentia by Anderson and Bender (1989). The oxidized Jamon suite granites crystallized at fO_2 conditions near the NNO and HITMQ (Wones, 1989) buffers and are similar to the magnetite-series granites of Laurentia (Anderson and Morrison, 2005). The dominant syenogranites of the Velho Guilherme Suite are ilmenite-series. The amphibole-bearing monzogranite of the Antonio Vicente complex (Velho Guilherme suite) and the Serra dos Carajás granites are magnetite-bearing granites but are also relatively reduced. The Serra dos Carajás and Velho Guilherme granites evolved in fO_2 conditions similar to those of the rapakivi granites of Laurentia and Fennoscandia and thus have affinities with the classic rapakivi series (Rämö and Haapala, 1995). Peraluminous two-mica granites, similar to those in Laurentia (Anderson and Morrison, 2005), have not been found in Carajás.

4. Granite classifications and their applicability to A-type rapakivi granites

The alphabetic classification, developed initially for I- and S-type granites of the Lachlan Fold Belt of

Table 2
Chemical compositions of representative samples of the Paleoproterozoic A-type granites of the Jamon Suite

	Jamon (1)				Redenção (2)						Musa (3)
	HBMzG	BMzG	BMcG	LMzG	CBAMzG	BHMzG	HBMzG	BMzG	BMzP	LMzG	BHMzG
	AU 391	AU 375	AU 397	AU 376	DCR 34	DCR 63A	JCR 09	JCR 01D	JCR 07	DCR 07	KM 144B
SiO_2 (wt.%)	71.12	73.71	75.47	75.97	66.10	71.10	70.70	74.20	74.40	76.00	69.18
TiO_2	0.72	0.35	0.17	0.10	1.20	0.60	0.44	0.30	0.22	0.12	0.64
Al_2O_3	12.42	12.36	12.50	13.70	13.10	13.50	14.20	13.30	13.10	13.10	13.21
Fe_2O_3	4.52*	2.79*	1.61*	0.28	3.47	2.19	1.24	1.31	1.01	0.65	4.69*
FeO	n.d.	n.d.	n.d.	0.38	3.36	1.54	2.03	0.62	0.53	0.31	n.d.
MnO	0.07	0.04	0.01	0.01	0.13	0.07	0.06	0.05	0.04	0.03	0.06
MgO	0.68	0.32	0.20	0.04	1.10	0.60	0.46	0.22	0.18	<0.10	0.88
CaO	2.40	1.21	0.64	1.00	2.80	2.10	1.60	1.10	0.67	0.55	2.37
Na_2O	3.37	3.27	3.47	3.87	3.70	3.70	3.50	3.50	3.40	3.10	3.59
K_2O	3.70	4.75	4.97	4.06	3.90	4.20	4.80	5.10	5.30	5.40	4.01
P_2O_5	0.32	0.20	0.13	0.01	0.42	0.22	0.14	0.05	0.04	0.01	0.32
LOI	0.30	0.70	0.62	0.57	0.32	0.38	0.35	0.31	0.73	0.17	0.53
Total	99.62	99.7	99.79	99.99	99.60	100.2	99.52	100.1	99.62	99.44	99.48
Ba (ppm)	1320	718	443	99	919	1498	1310	909	489	32	1056
Rb	100	230	281	159	151	139	193	204	281	396	172
Sr	246	118	61	41	241	332	271	196	122	27	232
Zr	397	283	164	57	686	377	353	258	240	126	299
Nb	19	21	21	17	29	16	20	21	24	21	16
Y	65	79	137	14	80	50	43	71	62	30	47
Ga	26	31	28	n.d.	26	26	25	23	27	27	19
Sc	13	7	2.5	n.d.	14	<10	15	10	<10	<10	9.3
Th	9	25	29	n.d.	<5	<5	<5	<5	<5	<5	23
U	3.7	n.d.	5.56	n.d.	<10	<10	<10	<10	<10	<10	n.d.
V	23	9	5	n.d.	53	22	14	<10	<10	<10	44
Cr	8	5	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	15
Co	5	n.d.	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	14
Ni	5	5	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	13
Cu	11	5	5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	11
Zn	69	48	36	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	58
La	89.75	101.0	155.4	n.d.	102.9	60.5	82.0	71.8	56.8	11.9	88.13
Ce	154.6	178.0	172.5	n.d.	196.5	120.9	146.7	139.7	114.4	31.9	152.3
Nd	71.77	67.4	99.5	n.d.	84.5	48.4	46.6	51.7	36.3	9.2	65.87
Sm	14.53	12.8	21.94	n.d.	14.9	8.1	8.4	9.3	6.6	1.8	12.99
Eu	2.65	1.6	1.88	n.d.	1.6	1.5	1.4	1.4	0.7	0.2	2.12
Gd	11.88	10.5	19.76	n.d.	11.8	6.3	6.0	7.6	5.0	1.3	10.43
Dy	10.71	10.2	18.84	n.d.	7.9	4.4	3.8	5.0	3.9	0.8	8.77
Er	6.14	6.5	10.09	n.d.	3.7	2.3	1.7	3.6	2.1	0.4	4.89
Yb	5.98	7.5	10.31	n.d.	2.9	1.8	1.2	2.8	1.9	0.4	4.71
Lu	0.87	1.0	1.53	n.d.	0.4	0.3	0.2	0.4	0.3	0.1	0.76
$FeO_t/(FeO_t+MgO)$	0.86	0.89	0.88	0.94	0.87	0.87	0.88	0.90	0.90	0.92	0.83
K_2O/Na_2O	1.10	1.45	1.43	1.05	1.05	1.14	1.37	1.46	1.56	1.74	1.12
Eu/Eu*	0.62	0.42	0.28	n.d.	0.35	0.61	0.57	0.49	0.37	0.29	0.56
$(La/Lu)_N$	10.71	10.48	10.54	n.d.	26.70	20.94	42.59	18.63	19.66	12.37	12.04

(1) Dall'Agnol et al. (1994); (2) Oliveira (2001); (3) Dall'Agnol et al. (1999b); (4) Almeida et al. (submitted for publication); n.d. = not determined; * = Fe_2O_3 as total; C = clinopyroxene; H = hornblende; B = biotite; MzG = monzogranite; McG = micro-granite; SG = syenogranite; P = porphyritic; L = leuco.

Australia (Chappell and White, 1974, 2001), was expanded (Collins et al., 1982; King et al., 1997, 2001) to include A-type granites (originally defined by Loiselle and Wones, 1979). This classification has been largely adopted around the world; it has, however, been more commonly used as a geochemical rather than genetic classification. There has also been dispute regarding the source of the granite magmas and tectonic settings inherent in this classification (e.g., Whalen et al., 1987; Pitcher, 1993; Frost et al., 2001).

In the Lachlan Fold Belt, A-type granites are subordinate relative to I- and S-type granites (Collins et al.,

				Bannach (4)				
HBMzG	BMzG	LMzG	LSG	CBHMzG	BHMzG	HBMzG	BMzP	LMzG
KM 32	CRE 37A	CRE 37B	CRE 140E	ADR 136I	ADR 67	ADR 241	ADR 45B	ADR 28B
71.80	72.62	74.97	76.20	58.12	70.39	72.36	75.70	76.86
0.45	0.38	0.20	0.08	2.41	0.56	0.42	0.33	0.15
13.08	12.66	12.35	12.28	9.17	13.09	12.75	11.11	11.45
3.41*	2.86*	1.95*	1.18*	6,87	2.71	2.09	1.90	1.23
n.d.	n.d.	n.d.	n.d.	8.86	1.00	0.95	0.64	0.10
0.04	0.07	0.02	n.d.	0.29	0.06	0.05	0.03	0.03
0.56	0.36	0.20	0.04	2.48	0.46	0.35	0.25	0.09
1.85	1.53	0.85	0.60	3.31	2.01	1.66	0.85	0.64
3.52	3.41	3.47	3.44	1.92	3.38	3.20	2.60	2.88
4.57	4.62	5.05	5.30	3.10	4.14	4.56	4.61	5.14
0.29	0.22	0.13	0.13	0.79	0.16	0.11	0.06	0.03
0.54	0.68	0.60	0.59	1.00	0.90	0.60	0.80	0.40
100.01	99.41	99.79	99.84	99.31	98.97	99.21	98.95	99.01
1053	698	216	282	427	1373.40	988.20	641.20	237.70
170	210	179	259	202	150.30	168.40	183.50	180.80
181	142	66	50	107	211.20	166.60	117.20	46.10
278	212	126	90	1683	394.70	317.60	276.40	125.40
14	20	19	12	65	21.90	21.30	10.10	17.20
34	46	22	7	234	55.00	57.50	27.50	22.20
23	23	23	14	26	20.30	19.40	18.60	18.70
7.9	5.4	3.7	1.7	33	9.00	8.00	3.00	2.00
25	35	75	39	15	18.90	22.50	41.20	13.00
n.d.	n.d.	n.d.	n.d.	7	2.80	3.30	4.20	2.40
26	16	5	5	129	21.00	11,00	6.00	<5
18	7	17	12	n.d.	n.d.	n.d.	n.d.	n.d.
16	13	19	20	n.d.	n.d.	n.d.	n.d.	n.d.
14	7	11	8	n.d.	n.d.	n.d.	n.d.	n.d.
8	5	5	11	n.d.	n.d.	n.d.	n.d.	n.d.
54	56	38	12	n.d.	n.d.	n.d.	n.d.	n.d.
61.15	87.91	173.6	33.61	157.90	88.90	99.70	197.00	35.60
108.1	140.1	198.5	54.72	378.90	185.30	210.20	409.80	66.40
44.28	47.20	46.15	14.30	206.80	70.40	75.50	103.90	23.40
9.0	8.76	6.75	2.85	43.80	12.20	13.20	11.80	4.00
1.55	1.28	0.81	0.52	2.43	2.32	1.80	1.29	0.60
8.45	6.79	5.21	3.22	39.32	10.26	10.17	6.70	3.51
5.84	5.98	3.48	1.44	36.72	9.08	9.45	4.51	3.57
3.34	3.76	2.48	1.15	21.53	5.42	5.57	2.62	2.22
3.37	4.31	3.33	1.49	17.90	4.84	4.54	2.53	2.35
0.65	0.86	0.71	0.34	2.58	0.74	0.69	0.44	0.38
0.85	0.88	0.90	0.96	0.86	0.88	0.89	0.90	0.93
1.38	1.35	1.46	1.54	1.61	1.22	1.43	1.77	1.78
0.54	0.51	0.42	0.52	0.18	0.63	0.47	0.44	0.49
9.77	10.61	25.38	10.26	6.33	13.18	15.75	55.85	10.87

1982; Whalen et al., 1987; King et al., 1997, 2001). King et al. (1997) emphasized the geochemical contrasts between true peralkaline and other A-type granites of the Lachlan Fold Belt and designated the latter as 'aluminous A-type granites' based on their metaluminous to weakly peraluminous character. However, King et al. (2001) suggested the abandon of this terminology. They also stated that the Lachlan A-type granites are distinguished from felsic I-type granites by a greater abundance of high-field-strength elements and that they were produced by high-temperature, partial melting of quartz-feldspathic crustal sources, with limited H_2O content, relatively low fO_2 and relatively high $(TiO_2 + FeO_t)/MgO$. Magnetite found in some of the Australian A-type

granites was interpreted as secondary, and most of the Wangrah Suite granites evolved under reduced conditions, below the FMQ buffer (King et al., 2001). The A-type granites of Lachlan show relatively limited variation and, except for the Watergums granite that contains 0.2% modal magnetite (Clemens et al., 1986), magnetite-series granites were not generally described from the area. Accordingly, the White and Chappell classification can be useful to distinguish between I-, S-, and A-type granites of Lachlan, but it does not discriminate different A-type granite groups described from elsewhere.

Ishihara (1977, 1981) proposed a non-genetic classification for granites on the basis of magnetite content and magnetic susceptibility. The magnetite-series granites have more than 0.1 vol.% of magnetite and the ilmenite-series granites are magnetite-free. This classification was developed for the granites of Japan and has been extended to the circum-Pacific orogenic belt and also to anorogenic environments (Takahashi et al., 1980; Ishihara, 1981; Anderson and Bender, 1989; Dall'Agnol et al., 1997a). The contrasts between these series are considered to be related to differences in oxygen fugacity during magma evolution, the magnetite-series granites being oxidized and the ilmenite-series reduced. This classification has been applied to the Mesoproterozoic A-type granites of Laurentia and Fennoscandia (Anderson and Cullers, 1999; Anderson and Morrison, 2005). It presents, however, some contradictory aspects that need discussion. As observed in the Carajás region, some A-type granites that clearly classify as oxidized magnetite-series according to the terminology of Ishihara can also have high FeO/(FeO+MgO) ratios in whole-rock, amphibole, and biotite; this indicates that they evolved at relatively reducing conditions, probably not far from the FMQ buffer. On the other hand, granites which formed at moderately reduced conditions, on or a little above FMQ, can have significant modal contents of magnetite. These granites were formed in fO_2 conditions between those of the ilmenite-series granites and the typical oxidized magnetite-series granites. Even granites and rhyolites with the classic fayalite+magnetite+quartz assemblage, that were unequivocally formed under low oxygen fugacity (FMQ; e.g., Frost, 1991), can have significant modal contents of magnetite (Galindo et al., 1995; Dall'Agnol et al., 1999d; McReath et al., 2002). These granites display magnetic susceptibility values that are higher than those of the ilmenite-series granites, which are devoid of magnetite. Hence not all magnetite-series granites of Ishihara (1981) have been evolved in oxidizing conditions and thus other aspects than Fe–Ti oxide minerals should be used to distinguish them from the calc-alkaline or oxidized A-type magnetite-series granites.

Eby (1990, 1992) scrutinized the trace element composition of A-type granites and identified significant differences in their signatures. He proposed to divide the A-type granites into two subgroups (A1 and A2) with contrasting petrogenesis. The oxidized A-type granites (see Anderson and Bender, 1989, for Laurentia; Dall'Agnol et al., 1999b, for Amazonia), the rapakivi granites of Fennoscandian shield, and the A-type granites of Lachlan, all display the geochemical characteristics of the A2 subgroup. In contrast, the White Mountain Series and the Shira Nigerian Younger A-type granites are both classified as A1 (see Dall'Agnol et al., 1999b).

Barbarin (1999) proposed tectonic, geological, and geochemical criteria to distinguish between different granite series. He identified strongly peraluminous (S-types and their variants), calc-alkaline orogenic, and arc or mid-ocean tholeiitic granitoids. However, on that classification, A-type granites are represented only by peralkaline granites of inferred mantle origin. The metaluminous to mildly peraluminous A-type granites, represented by the rapakivi and similar A-type granites of crustal origin (Rämö and Haapala, 1995; Dall'Agnol et al., 1999a; Bettencourt et al., 1999) are not clearly represented in Barbarin's classification.

Patiño Douce (1999) distinguished six groups of felsic 'granitic' rocks on the basis of major element composition, petrogenesis, and tectonic setting: peraluminous leucogranites, S-type granites, peraluminous Cordilleran granites, calc-alkaline granites, metaluminous alkali-rich granites (MAGS), and rhyolites associated with continental flood-basalt provinces (FBRS). The MAGS are predominantly metaluminous A-type granites and rhyolites, including rapakivi granites. Strongly peralkaline granites and their volcanic equivalents as well as strongly peraluminous topaz rhyolites are excluded from MAGS by Patiño Douce (1999). The FBRS are distinctly metaluminous Fe-rich rocks that share some characteristics with MAGS. The clear differences between MAGS and peralkaline granites (Patiño Douce, 1999) require a refined classification of these two A-type granite groups. Patiño Douce's criteria to distinguish strongly peraluminous topaz rhyolites from MAGS are less evident, not least in view of the fact that topaz-bearing granites, similar in mineralogy and geochemistry to topaz rhyolites (Christiansen et al., 1986; Christiansen, 2003), are commonly associated with the more evolved facies of rapakivi granites (Haapala, 1977, 1995; Dall'Agnol et al., 1999a; Bettencourt et al., 1999; Lenharo et al., 2002). According to Patiño Douce (1999), peraluminous leucogranites are the only group that represents pure anatectic crustal melts–the other groups correspond to crystal-rich magmas with residual phases or hybrid melts resulting

from interaction of crustal rocks with mafic mantle-derived magmas.

Frost et al. (2001) proposed a non-genetic classification for granitic rocks considering their major element compositions. Their classification scheme uses three major element chemical parameters, the Fe-number (Fe or Fe*), the modified alkali-lime index (MALI) and the aluminum saturation index (ASI) to distinguish 16 different kind of granites independent of their magma sources or tectonic environment. The Fe* parameter [FeO_t/(FeO_t+MgO)] is a good discriminant between A-type and Cordilleran granites and also quite useful for a preliminary identification of A-type granites. In the FeO_t/(FeO_t+MgO) vs. SiO_2 diagram proposed by Frost et al. (2001) (Fig. 2d), A-type granites plot systematically in the ferroan field (high Fe*). However, in the Na_2O+K_2O-CaO (MALI) vs. SiO_2 diagram (Fig. 2b), A-type granites spread across several fields. This is probably due to the fact that whole-rock Al_2O_3 content, commonly employed as a discriminating parameter (Irvine and Baragar, 1971; Ringwood, 1975; Wilson, 1989) is not considered in MALI.

Most of the classifications reviewed above do not discriminate the different A-type granite groups and some of them are unable to distinguish oxidized, magnetite-series A-type granites from the orogenic calc-alkaline and I-type granites.

5. Geochemical distinction of oxidized A-type granites

As emphasized by Patiño Douce (1999) and Frost et al. (2001), it is profitable to use major element chemical composition for granite classification, whereas genetic connotations should be left out. We will take the classification scheme of Frost et al. (2001) and the group of metaluminous, alkali granites (MAGS) of Patiño Douce (1999) as a starting point for our refined geochemical characterization of A-type granites. The scheme of Patiño Douce (1997) will also be used, mainly to differentiate between A-type and calc-alkaline granitoids.

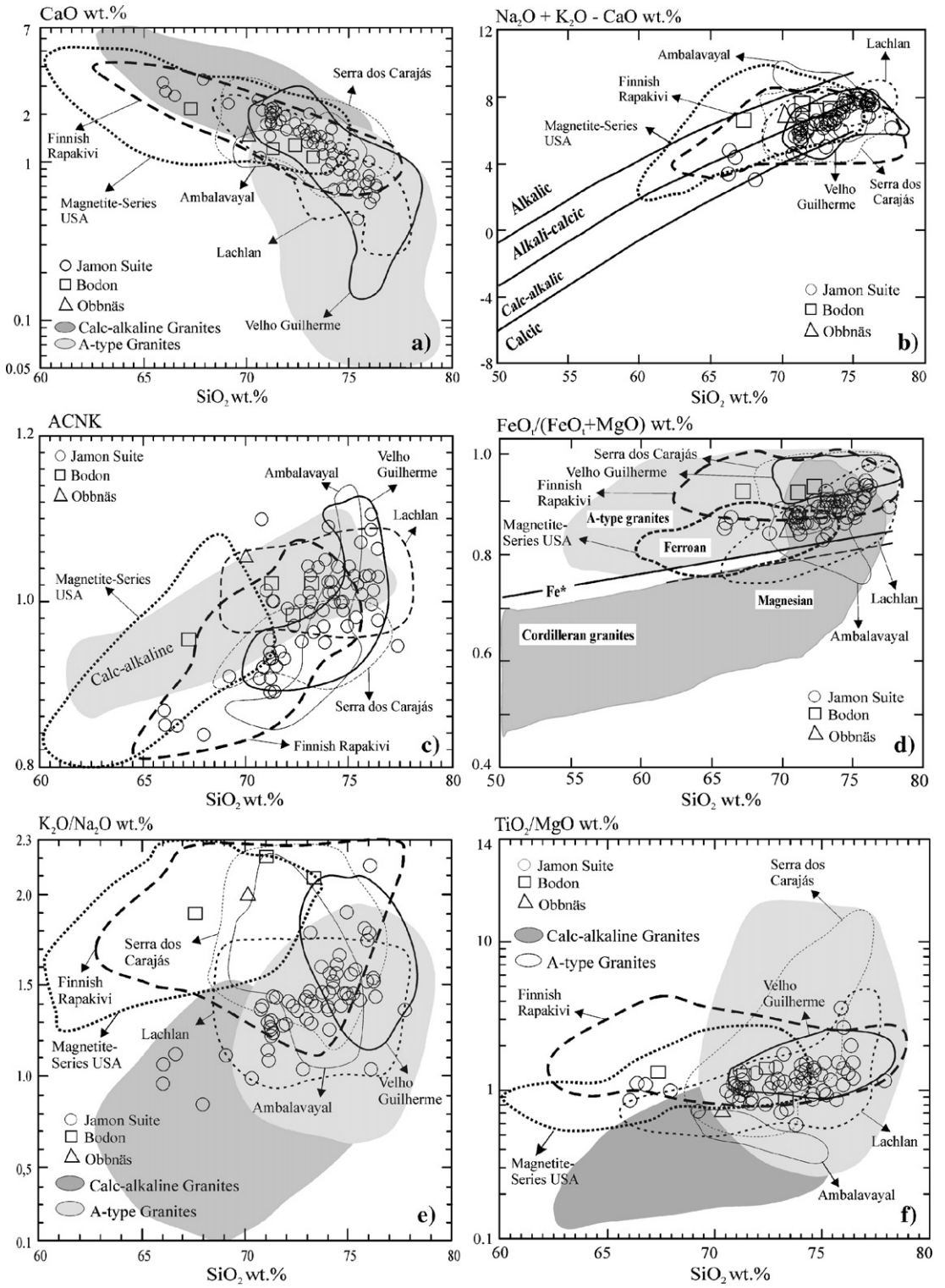
In search of distinctive geochemical characteristics of oxidized, rapakivi A-type granites, we have employed a data set (available on request from the authors) with representative geochemical data from (1) the Carajás region granites (Jamon, Serra dos Carajás, and Velho Guilherme suites, Dall'Agnol et al., 2005); (2) the Finnish rapakivi granites (Wiborg area, Rämö, 1991, Rämö and Haapala, 1995; Bodom and Obbnäs plutons, Kosunen, 1999—the Bodom and Obbnas plutons were chosen because they dominant facies show significant differences in whole-rock FeO_t/(FeO_t+MgO) ratios); (3) the Mesoproterozoic magnetite-series granites of Laurentia (Anderson and Bender, 1989); (4) the A-type granites of the Lachlan Fold Belt (King et al., 1997, 2001); (5) the Ambalavayal A-type granite (Rajesh, 2000); (6) calc-alkaline Cordilleran granitoids (Sierra Nevada and Tuolumne batholiths; samples with more than 60 wt.% of SiO_2 from the data set of Frost et al., 2001). Peralkaline granites have not been included, because they form an independent group of A-type granites. In the plots presented here, the Jamon suite samples, corresponding to the oxidized A-type granites of Carajás, are represented individually. The other suites are represented as fields, except for the average compositions of the main granite facies of the Bodom and Obbnäs plutons (Kosunen, 1999).

The data are shown in a selection of the diagrams proposed by Patiño Douce (1997) and Frost et al. (2001) in Fig. 2. In the CaO vs. SiO_2 plot (Fig. 2a), the selected A-type granites have lower CaO contents than calc-alkaline granites but define fields that are almost parallel to the calc-alkaline field. In general, the Jamon suite granites plot in the area of overlap between the calc-alkaline and A-type fields, and extend into the A-type field (silica-rich samples) and the calc-alkaline field (silica-poor samples). They also plot almost in the same area as the Finnish rapakivi granites and the magnetite-series granites of the United States. The reduced Velho Guilherme suite granites of Carajás plot in the A-type field of Patiño Douce (1997). In the Na_2O+K_2O-CaO vs. SiO_2 diagram (Fig. 2b), the A-type granite suites plot preferentially in the calc-alkalic and alkali-calcic fields (Frost et al., 2001). The Jamon suite samples are concentrated in the calc-alkalic field. The magnetite-series granites of the United States are enriched in alkalies compared to the Jamon granites and in part fall into the alkali field. In the A/CNK vs. SiO_2 diagram (Fig. 2c), the fields of A-type granites and calc-alkaline granites are partially superposed. It is clear that these diagrams do not clearly discriminate A-type granites and calc-alkaline granites.

On the other hand, in the FeO_t/(FeO_t+MgO) vs. SiO_2 (Frost et al., 2001) and K_2O/Na_2O vs. SiO_2, TiO_2/MgO vs. SiO_2 (Patiño Douce, 1997) diagrams (Fig. 2d,e,f), the selected A-type granites are concentrated in the A-type and ferroan fields, and are better discriminated from calc-alkaline and Cordilleran granites. Compared to the latter, A-type granites show generally higher FeO_t/(FeO_t+MgO), K_2O/Na_2O, and TiO_2/MgO. Some of the differences in the selected A-type granite fields and the fields of Patiño Douce (1997) relate to the fact that some peralkaline granites are included in the indicated A-type field (Patiño Douce, 1997; see NK/A plot,

his Fig. 1) and that dispersed samples with less than 70 wt.% SiO_2 are not represented in our schematic field.

The oxidized Jamon suite granites display geochemical trends that are similar to those of the magnetite-series granites of Laurentia (Fig. 2a to f), however the lower K_2O/Na_2O and higher SiO_2 of Jamon



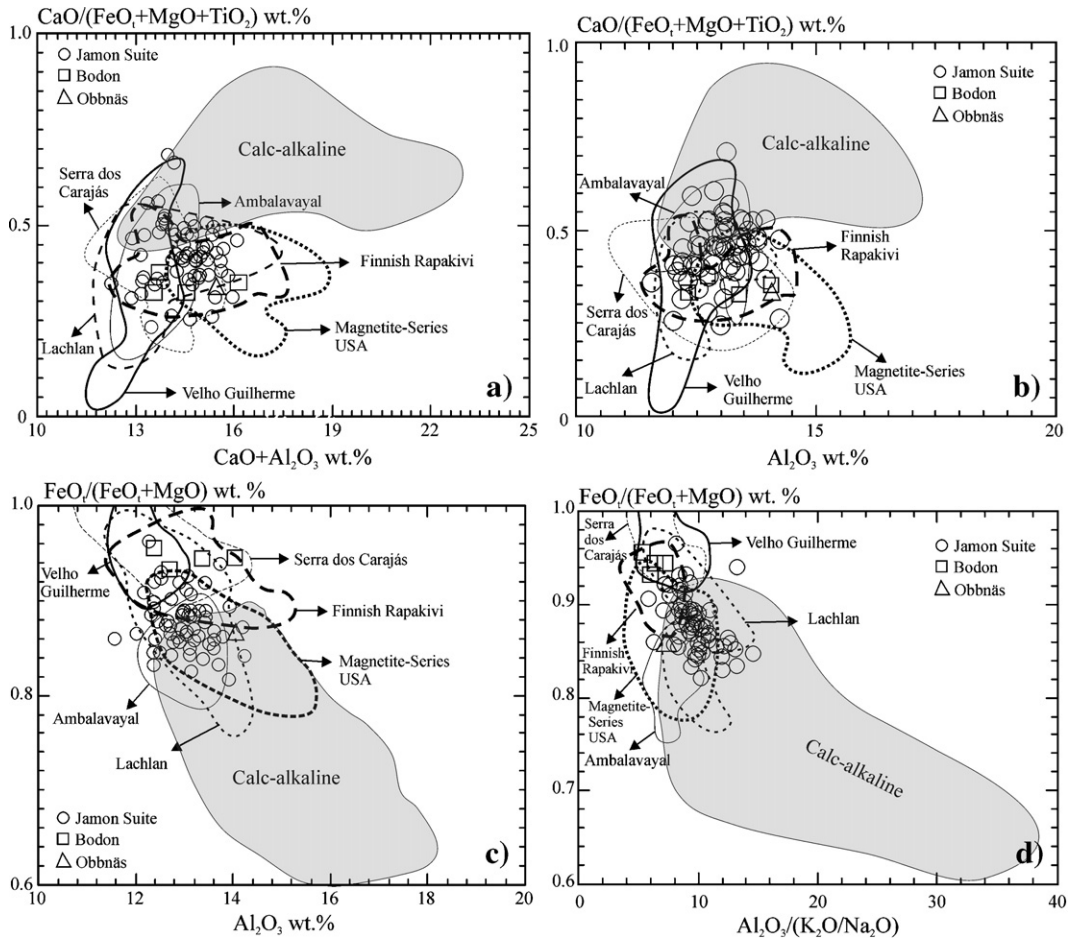


Fig. 3. Whole-rock CaO/(FeOt+MgO+TiO$_2$) vs. CaO+Al$_2$O$_3$ (a), CaO/(FeOt+MgO+TiO$_2$) vs. Al$_2$O$_3$ (b), FeOt/(FeOt+MgO) vs. Al$_2$O$_3$ (c), and FeOt/(FeOt+MgO) vs. Al$_2$O$_3$/(K$_2$O/Na$_2$O) (d) diagrams showing composition of representative oxidized and reduced A-type granites compared with calc-alkaline granites. Calc-alkaline fields are based on Sierra Nevada and Tuolumne granitoids with >60 wt.% of SiO$_2$ (Frost et al., 2001). Data sources from A-type granites as in Fig. 2.

distinguish this suite from the Laurentian granites in some of the plots. The fields of rapakivi granites and the reduced Velho Guilherme and Serra dos Carajás granites are similar to those of the oxidized granites, but their FeO$_t$/(FeO$_t$ +MgO) and TiO$_2$/MgO ratios are generally higher than in the A-type oxidized granites (Fig. 2d,f). The Ambalavayal granites and some samples of the Lachlan Belt A-type granites show the lowest FeO$_t$/(FeO$_t$+ MgO) and fall in both the magnesian and ferroan fields (Fig. 2d). The Ambalavayal granites display also the lowest TiO$_2$/MgO ratios (Fig. 2f).

Patiño Douce (1999) compared Cordilleran granites, metaluminous A-type granites and basalt plateau rhyolites with the composition of experimental melts from varied sources. He showed that the CaO/(FeO$_t$+ MgO+TiO$_2$) ratio and CaO+Al$_2$O$_3$ contents are useful

Fig. 2. Whole-rock (a) CaO vs. SiO$_2$, (b) Na$_2$O+K$_2$O−CaO vs. SiO$_2$, (c) [Al$_2$O$_3$/(CaO+Na$_2$O+K$_2$O)]$_{Mol}$ vs.SiO$_2$, (d) FeOt/(FeOt+MgO) vs. SiO$_2$, (e) K$_2$O/Na$_2$O vs. SiO$_2$, and (f) TiO$_2$/MgO vs. SiO$_2$ diagrams showing composition of representative A-type granites compared with calc-alkaline granites. A-type and calc-alkaline granite fields in (a), (e), and (f) from Patiño Douce (1997); alkalic, alkalic-calcic, calc-alkalic, and calcic fields in (b) and Fe* divide line, magnesian Cordilleran granites and ferroan A-type granites fields in (d) are from Frost et al. (2001a). Data sources: Rämö and Haapala (1995) [Finnish rapakivi plutons from the Wiborg area]; Kosunen (1999) [Bodom and Obbnäs rapakivi plutons, southern Finland]; Anderson and Bender (1989) [Mesoproterozoic magnetite-series granites of the United States]; King et al. (1997, 2001) [Lachlan Fold Belt A-type granites]; Rajesh (2000) [Ambalavayal granites]; Dall'Agnol et al. (2005, and references therein) [Carajás A-type granite suites?Jamon (oxidized), Serra dos Carajás (moderately reduced), and Velho Guilherme (reduced); Frost et al. (2001) (calc-alkaline field in (c), Sierra Nevada and Tuolumne granitoids with >60 wt.% of SiO$_2$].

in discriminating A-type and calc-alkaline granites. Accordingly, we have plotted the selected granites in the $CaO/(FeO_t+MgO+TiO_2)$ vs. $CaO+Al_2O_3$ diagram (Fig. 3a). Clearly distinct fields for the calc-alkaline granites and A-type granites emerge—this reflects the lower CaO and Al_2O_3 contents of A-type granites and stresses the contrast in Al_2O_3 content between these granite types. In fact, Al_2O_3 content is a critical parameter in the characterization of calc-alkaline series (Irvine and Baragar, 1971; Ringwood, 1975; Wilson, 1989) and it should be considered in the geochemical distinction of these two granite series. It turns out that the $CaO/(FeO_t+MgO+TiO_2)$ vs. Al_2O_3 diagram (Fig. 3b) offers a good discrimination between A-type and calc-alkaline granites. However, in these diagrams (Fig. 3a,b), the fields of oxidized and reduced A-type granites are largely superposed, and these diagrams are not useful in distinguishing these two A-type granite groups.

As the next step, Al_2O_3 was plotted against $FeO_t/(FeO_t+MgO)$ (Fig. 3c), a parameter for evaluation of the oxidizing character of magmatic rocks (Frost, 1991; Emslie, 1991; Frost et al., 2001; Anderson and Morrison, 2005; see Fig. 2d). This plot discriminates A-type and calc-alkaline granites, and allows a clear distinction between oxidized and reduced A-type granites. Due to their relatively low $FeO_t/(FeO_t+MgO)$ ratios, the Jamon suite samples and the magnetite-series granites of the United States are partially superposed with the calc-alkaline granite field. The $FeO_t/(FeO_t+MgO)$ vs. $Al_2O_3/(K_2O/Na_2O)$ diagram (Fig. 3d) employs some prominent geochemical parameters for the distinction of A-type granites (high in $FeO_t/(FeO_t+MgO)$ and K_2O/Na_2O) and calc-alkaline granites (high in Al_2O_3). This diagram discriminates calc-alkaline and A-type granites and also allows a good distinction between oxidized and reduced A-type granites.

It is concluded that: (1) the $FeO_t/(FeO_t+MgO)$ vs. SiO_2, K_2O/Na_2O vs. SiO_2, and TiO_2/MgO vs. SiO_2 diagrams (Fig. 2d,e,f), as well as the new proposed $CaO/(FeO_t+MgO+TiO_2)$ vs. $CaO+Al_2O_3$ and $CaO/(FeO_t+MgO+TiO_2)$ vs. Al_2O_3 diagrams (Fig. 3a,b), are well suited to distinguish between A-type and calc-alkaline granites; (2) the oxidized A-type granites are geochemically distinct from I-type, calc-alkaline or Cordilleran granitoids and similar in most geochemical aspects to typical A-type, including rapakivi, granites; and (3) the $FeO_t/(FeO_t+MgO)$ vs. Al_2O_3 and $FeO_t/(FeO_t+MgO)$ vs. $Al_2O_3/(K_2O/Na_2O)$ diagrams (Fig. 3c, d) can be used to distinguish oxidized and reduced A-type granites, as well as for general discrimination of A-type from calc-alkaline granites.

6. $FeO_t/(FeO_t+MgO)$ ratio vs. magnetite-series and ilmenite-series

Anderson and Morrison (2005) stated that whole-rock $FeO_t/(FeO_t+MgO)$ ratios of magnetite-series granites of Laurentia typically range between 0.80 and 0.88, while those of ilmenite-series granites are generally higher (>0.88). Similar values (Figs. 2d, 3c,d) are shown by, respectively, the oxidized Jamon granites (0.83 to 0.94; Dall'Agnol et al., 1999c; Oliveira, 2001; Dall'Agnol et al., 2005) and the reduced Velho Guilherme and moderately reduced Serra dos Carajás granites (0.89 to 0.99; Teixeira, 1999; Dall'Agnol et al., 2005). However, some ilmenite-series granites of Laurentia (Anderson and Morrison, 2005; their Fig. 2) and some Finnish rapakivi granites (Fig. 3c,d) display whole-rock $FeO_t/(FeO_t+MgO)$ ratios lower than 0.88 and can not be distinguished from magnetite-series by this parameter. The Bodom and Obbnäs plutons are good examples of the contrasts in whole-rock $FeO_t/(FeO_t+MgO)$ ratios observed in rapakivi granites (Fig. 2d). The Bodom granites have higher whole-rock, biotite, and amphibole $FeO_t/(FeO_t+MgO)$ compared to Obbnäs (Kosunen, 1999, 2004; see Dall'Agnol et al., 2005). The dominant granitic facies of Obbnäs contains primary titanite and undefined iron oxide minerals as accessory minerals (Kosunen, 1999) and has whole-rock $FeO_t/(FeO_t+MgO)$ similar to those of Jamon and magnetite-series granites of Laurentia (Fig. 3c,d). However, $FeO_t/(FeO_t+MgO)$ in biotite and amphibole from Obbnäs is high (~0.85–0,80; Kosunen, 2004) and similar to what is observed for moderately reduced A-type granites. This suggests that whole-rock and mafic mineral $FeO_t/(FeO_t+MgO)$ ratios must be employed with caution to define the reduced or oxidized character of A-type granites. There is a partial overlap between the fields of rapakivi granites, representative of the ilmenite-series, and oxidized, magnetite-series granites (Fig. 3c,d). This indicates that, for granites with whole-rock $FeO_t/(FeO_t+MgO)$ ratios near the limit for both series (0.88, as proposed by Anderson and Morrison, 2005), other aspects besides this ratio need to be considered in search of magmatic fO_2 values. The identities and modal contents of Fe–Ti oxide minerals will be extremely relevant in this respect (see Ishihara, 1981; Frost, 1991; Dall'Agnol et al., 1997a).

Another aspect of the same problem is illustrated by some A-type granites of Carajás, e.g., the Cigano granite (Dall'Agnol et al., 2005), which contain magnetite and are classified as magnetite-series, but also display very high whole-rock, biotite, and amphibole $FeO_t/(FeO_t+MgO)$ ratios, indicating crystallization in relatively reducing conditions. This suggests that the magnetite-

series and ilmenite-series granites, as originally defined by Ishihara (1977, 1981), and, respectively, oxidized and reduced A-type granites, cannot always be considered strictly equivalent.

The A-type granites of the Lachlan Fold Belt have been generally interpreted as reduced (see King et al., 1997, 2001). However, whole-rock $FeO_t/(FeO_t+MgO)$ ratios in these granites tend to be lower than in other A-type granites (see Frost et al., 2001) and their fields (Fig. 3c,d) are superposed with both ilmenite-series and magnetite-series granites. This suggests that the Lachlan A-type granites were crystallized from both reduced and oxidized magmas. This hypothesis is reinforced by the content (0.2% modal) of early magmatic magnetite in the Watergums granite (Clemens et al., 1986; see their Fig. 1).

The Ambalavayal granites contain primary titanite and magnetite and whole-rock $FeO_t/(FeO_t+MgO)$ ratios similar or even lower than those of oxidized A-type granites (0.76 to 0.90; Rajesh, 2000; Fig. 3c,d). They evolved in oxidizing conditions, around or above NNO (Rajesh, 2000), and should also be classified as magnetite-series (Ishihara, 1981). However, the $FeO_t/(FeO_t+MgO)$ ratios in amphibole and biotite are extremely high (>0.95; Rajesh, 2000) and coincident with those shown by ilmenite-series granites (Anderson and Bender, 1989; Anderson and Smith, 1995; Rämö and Haapala, 1995; Frost and Frost, 1997; Frost et al., 1999; Anderson and Morrison, 2005). The reason for this ambiguous behavior is not clearly understood.

It is concluded that: (1) all magnetite-bearing granites are not necessarily oxidized and there is not a strict equivalence between the magnetite-series and ilmenite-series classification of Ishihara (1981) and, respectively, reduced and oxidized granites in general; (2) whole-rock and mafic mineral $FeO_t/(FeO_t+MgO)$ ratios must be employed with caution to define the reduced or oxidizing character of A-type granites near the boundary of ilmenite and magnetite-series granites; (3) definition of nature and modal contents of Fe–Ti oxide minerals of A-type granites, coupled with mineralogical and geochemical data, are relevant for estimation of fO_2 conditions during magma crystallization.

7. Experimental constraints on the origin of oxidized A-type granites

Clemens et al. (1986) carried out crystallization experiments on the Watergums A-type granite at a pressure of 1 kbar, fO_2 at FMQ+0.3 and variable water contents in melt. The studied rock is a low-CaO (1.24 wt.%) syenogranite containing modal biotite, amphibole, and magnetite (1.5, 0.7, and 0.2 vol.%, respectively). The low pressure favored water saturation at relatively low water content in melt (~4 wt.% H_2O) and, associated with low CaO content (see experimental results at 2 kbar in the AB422 granite of Wangrah Suite with similar CaO content; Klimm et al., 2003), inhibited amphibole crystallization in experiments. The liquidus phases were magnetite or quartz, depending on the water content, both followed by plagioclase and at lower temperature clinopyroxene. Clemens et al. (1986) estimated high temperatures (>830 °C) and appreciable water contents (2.4 to 4.3 wt.%) for the Watergums granite magma.

Patiño Douce and Beard (1995) performed vapor-absent dehydration melting and some coupled crystallization experiments of a biotite gneiss and a quartz amphibolite from 3 to 15 kbar. The low pressure experiments (3 to 5 kbar) were performed at fO_2 above NNO and those at higher pressures (7 to 15 kbar) at fO_2 below FMQ. In the dehydration melting experiments with the biotite gneiss (2.1 wt.% of CaO), the major mafic residual phase for pressures between 3 and 10 kbar is orthopyroxene, accompanied by garnet at 12.5 kbar, and by garnet and clinopyroxene at 15 kbar (Patiño Douce and Beard, 1995). In similar experiments, the quartz amphibolite (7.6 wt.% of CaO) contained orthopyroxene and clinopyroxene as the major residual phases for all pressures, accompanied by garnet at 12.5 and 15 kbar. These results indicated that, independent of pressure, orthopyroxene and clinopyroxene are important residual phases for CaO-enriched sources, while for low-CaO compositions, clinopyroxene is found as a major residual phase only at high pressure (~15 kbar). It is also worth noting that at low pressure (3 to 5 kbar) and fO_2 above NNO, the molar $Al_2O_3/(MgO+FeO)$ ratio decreased with increasing pressure (Patiño Douce and Beard, 1995, their Fig. 13). This suggests that, in oxidizing conditions, melts generated by dehydration melting at low pressures (≤4 kbar) should contain higher Al_2O_3 than those formed at more elevated pressures. If an origin by dehydration melting of crustal igneous sources is true for oxidized, metaluminous A-type granites, this indicates that the low Al_2O_3 contents (Fig. 3b, c) shown by these A-type granites will probably not be favored by low pressure melting.

Patiño Douce (1997) performed dehydration melting experiments at 950 °C, fO_2 1 log unit below FMQ, and pressures of 4 and 8 kbar on calc-alkaline hornblende–biotite granitoids from Sierra Nevada. Generated melt volume decreased from tonalite (~40 to 30%) to granodiorite (~20 to 15%) and with increasing pressure. At 4 kbar, melting reactions produced neoblastic Ca-rich plagioclase, abundant orthopyroxene, and scarce

clinopyroxene. At 8 kbar, clinopyroxene was abundant, orthopyroxene rare, and plagioclase growth negligible. Melt compositions are similar to A-type granites, but those obtained at 4 kbar have more definite A-type characteristics than those formed at 8 kbar (Patiño Douce, 1997). This difference was attributed to the presence of plagioclase+orthopyroxene as dominant residual phases at shallow pressure (≤4 kbar) dehydration melting, in contrast to the dominance of clinopyroxene at higher pressure (~8 kbar). Patiño Douce concluded that low pressure dehydration melting of calc-alkaline granitoids is a likely origin for 'high-silica metaluminous A-type granites', including rapakivi granites, and that the A-type chemical characteristics are lost in melts generated in the deep crust.

Patiño Douce (1999) presented a similar reasoning to explain the origin of his group of metaluminous, alkali-rich granites (MAGS). These A-type granites and rapakivi granites were discussed together with the rhyolites associated with continental flood-basalt provinces (FBRS). Patiño Douce (1999) emphasized that these 'silicic igneous rocks of shallow origin' have several geochemical characteristics in common. He presented geochemical diagrams where MAGS and FBRS are compared, among others, to calc-alkaline granitoids and compositional ranges of experimental metasediment-derived melts, and low pressure melts of calc-alkaline granitoids. Patiño Douce (1999) concluded that metaluminous A-type and rapakivi granites and rhyolites associated with continental flood-basalts may be the products of low pressure melting of calc-alkaline rocks and that varying degrees of hybridization with basalts played an important role in their origin.

The MAGS, FBRS, and CAGS (calc-alkaline granites) of Patiño Douce (1999) are plotted together with A-type granites on the CaO/Al_2O_3 vs. $CaO+Al_2O_3$ and $CaO/(FeO_t+MgO+TiO_2)$ vs. $CaO+FeO_t+MgO+TiO_2$ diagrams (Fig. 4a,b). The A-type granite fields are disposed parallel to the FBRS field, partially superposed with the MAGS field, and clearly separated from the CAGS field. Oxidized and reduced A-type granites (e.g., the Jamon, Serra dos Carajás, and Velho Guilherme suites) do not define distinct fields in these diagrams and the fields of rapakivi granites, magnetite-series from the United States and Jamon are largely coincident. A-type granites follow the reaction curves for low pressure hybridization of calc-alkaline granites with high-Al olivine tholeiites and also the low pressure (≤5 kbar) reaction curves for melt compositions produced by hybridization of high-Al olivine tholeiite with metagraywacke (Patiño Douce, 1999) (Fig. 4a,b). This suggests that plagioclase and orthopyroxene should be dominant residual phases of A-type magma sources. At the same time, it does not favor the formation of reduced and oxidized A-type granites at different pressures.

Dall'Agnol et al. (1999c) performed crystallization experiments on a hornblende–biotite monzogranite (2.2 wt.% CaO) of the Jamon suite at 3 kbar, varying

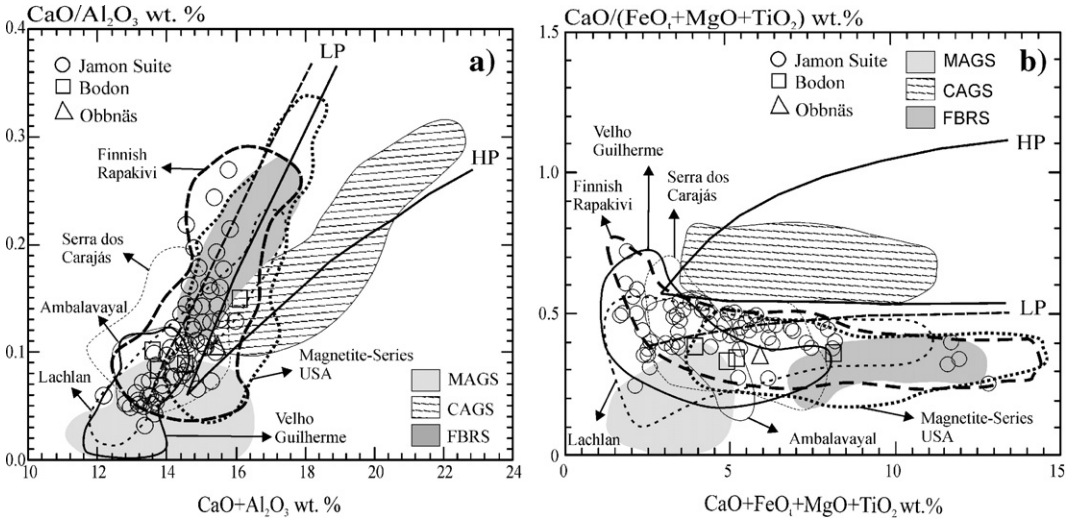


Fig. 4. Whole-rock CaO/Al_2O_3 vs. $CaO+Al_2O_3$ (a) and $CaO/(FeOt+MgO+TiO_2)$ vs. $CaO+FeOt+MgO+TiO_2$ (b) diagrams showing composition of representative oxidized and reduced A-type granites compared with calc-alkaline granites (CAGS), metaluminous alkali-rich granites (MAGS), and rhyolites associated with continental flood-basalts provinces (FBRS) (fields from Patiño Douce, 1999). Data sources for A-type granites as in Fig. 2. The dashed lines are reaction curves for low pressure hybridization of calc-alkaline granites with high-Al olivine tholeiites, with production of plagioclase+orthopyroxene. The solid lines labeled LP and HP imply melt compositions that would be produced by hybridization of high-Al olivine tholeiite with metagraywacke, at low pressure (LP, ≤5 kbar) or at high pressure (HP, 12 to 15 kbar) (Patiño Douce, 1999).

fO_2 (at NNO+2.5 and NNO−1.5) and water content in melt. In reducing conditions, clinopyroxene and orthopyroxene were the liquidus phases independent of water content. In oxidizing conditions, orthopyroxene was stable only at low H_2O content (<4 wt.%) and high temperatures. At higher water contents, clinopyroxene and plagioclase were the liquidus phases. Amphibole was stable only for liquids containing >4 wt.% of water, and its crystallization was thus strongly dependent on melt water contents (see Naney, 1983; Dall'Agnol et al., 1999c; Klimm et al., 2003). The amphibole probably derived from peritectic reactions between clinopyroxene± orthopyroxene and melt. The results obtained by Dall'Agnol et al. (1999c) indicate that, besides pressure, fO_2 and water content in the melt also exert a strong influence on the nature of liquidus phases and, therefore, on the residual phases of A-type magmas produced by dehydration melting. Moderately high water contents (>4 wt.%) and oxidizing conditions should inhibit the presence of orthopyroxene in the residue and favor that of clinopyroxene. In consequence, the A-type magmas generated under these conditions should be oxidized and have similar geochemical characteristics to the high pressure (~8 kbar) magmas derived from calc-alkaline sources of Patiño Douce (1997, 1999). Dall'Agnol et al. (1999c) also verified that Fe/(Fe+Mg) in experimental mafic phases decreases with increasing temperature and fO_2. They estimated a 4 to 6 wt.% of water content for the Jamon hornblende–biotite monzogranite and dacite porphyry magmas and a crystallization at NNO+0.5 and temperatures between 900 and ~700 °C. Dall'Agnol et al. (1999b,c) also suggested that the Jamon magma could have been derived by relatively high pressure (>6 kbar) dehydration melting of an Archean source geochemically similar to a sanukitoid biotite–hornblende quartz diorite.

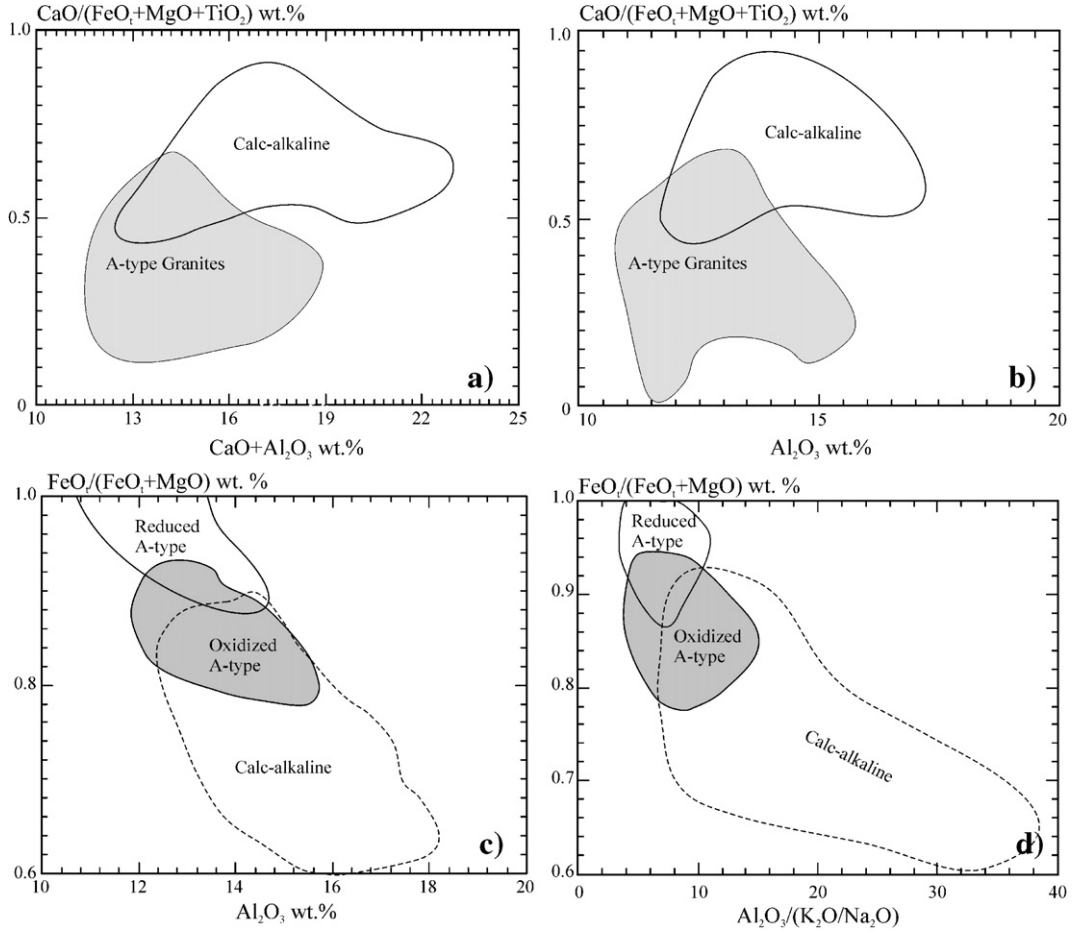


Fig. 5. Whole-rock CaO/(FeOt+MgO+TiO_2) vs. CaO+Al_2O_3 (a), CaO/(FeOt+MgO+TiO_2) vs. Al_2O_3 (b), FeOt/(FeOt+MgO) vs. Al_2O_3 (c), and FeOt/(FeOt+MgO) vs. Al_2O_3/(K_2O/Na_2O) (d) diagrams showing the compositional fields of calc-alkaline and A-type granites (a, b) and reduced and oxidized A-type granites and calc-alkaline granites (c, d). All fields were defined on the basis of data presented in Fig. 3.

Two hornblende–biotite granites (AB412 and AB422) of the Wangrah suite of the Lachlan Fold Belt were studied experimentally by Klimm et al. (2003) at 2 kbar, fO_2 between NNO and NNO − 1.05, temperature between 900 and 700 °C, and for various melt H_2O contents. The AB412 granite is enriched in CaO (1.93 wt.%) and modal amphibole compared to the AB422 granite (CaO = 1.31 wt.%). Obtained liquidus temperatures were high (900 to 850 °C) and orthopyroxene and plagioclase were the liquidus phases for both compositions. Initial water content in the original magma of AB412 was estimated to be 2 to 3 wt.% H_2O. Klimm et al. (2003) suggested that the geologically relevant conditions for the Wangrah granites' crystallization were $fO_2 < NNO - 2.2$. They observed also that Fe/(Fe + Mg) in experimental orthopyroxene, amphibole, and biotite decreased with increasing fO_2 and temperature and, in the case of orthopyroxene, also with increasing wt.% H_2O in melt.

The absence of clinopyroxene in the experimental phases of the Wangrah granites is noteworthy. In this aspect, they contrast with the results obtained on the Jamon granite. This difference could possibly be due to the higher CaO content and more oxidizing conditions of the Jamon granite. This indicates the relevance of source composition and fO_2, in determining the nature of residual phases during dehydration melting.

In summary, experimental evidence suggests that the geochemical signature of A-type granites is not dependent only on the pressure of melting. Source composition and fO_2 conditions also exert a strong influence on the composition of generated magmas. These parameters are extremely relevant for the definition of the nature of residual phases during dehydration melting of crustal sources. Another important factor is water content, which is also related to the nature of the magma source, and is determinant for the crystallization of water-bearing silicates (e.g., amphibole).

Contrasts in crustal sources (including water content) and fO_2, associated with varying pressure may explain the geochemical characteristics of oxidized and reduced A-type granites.

8. Conclusions

Geochemical data demonstrate that, whatever the nature of magmatic processes involved in the origin of oxidized A-type granites is, these processes are certainly able to produce the dominant characteristics of A-type granites. This is shown by the fact that oxidized A-type granites are clearly distinguished from calc-alkaline Cordilleran granites in several major elements diagrams (Figs. 2d,e,f, 3a,b) and define fields largely coincident with those of reduced A-type granites. Besides the $FeO_t/(FeO_t + MgO)$ vs. SiO_2 (Frost et al., 2001), K_2O/Na_2O vs. SiO_2, TiO_2/MgO vs. SiO_2 (Patiño Douce, 1997) diagrams (Fig. 2d,e,f), the $CaO/(FeO_t + MgO + TiO_2)$ vs. $CaO + Al_2O_3$ and $CaO/(FeO_t + MgO + TiO_2)$ vs. Al_2O_3 diagrams can be used to distinguish A-type and calc-alkaline granites (Fig. 5a,b). Oxidized and reduced A-type granites are better discriminated in the $FeO_t/(FeO_t + MgO)$ vs. Al_2O_3 and $FeO_t/(FeO_t + MgO)$ vs. $Al_2O_3/(K_2O/Na_2O)$ diagrams (Fig. 5c,d). We propose the two latter diagrams to distinguish between oxidized and reduced A-type granites. Preferentially, geochemical characterization should be accompanied by petrographic, Fe–Ti oxide, and magnetic susceptibility studies.

It is also concluded that all magnetite-bearing granites are not necessarily oxidized and a strict correspondence between oxidized and reduced A-type granites and, respectively, magnetite-series and ilmenite-series granites is not observed.

We have argued that oxidized granites like those of the Jamon suite and the Mesoproterozoic magnetite-series of the United States are better classified as A-type. It is also suggested that the classic rapakivi granites are more commonly ilmenite-series, reduced A-type granites. However, the relationship between oxidized A-type and rapakivi granites remains unresolved. In a classification scheme proposed for Laurentia–Baltica, the magnetite-series and ilmenite-series granites are spatially separated, implying broad regional changes in the composition of the lower crust sources of these granites (Anderson and Morrison, 2005). However, the A-type granites of Carajás region display near identical ages, occur in the same crustal province, and the processes involved in their origin are considered to be similar. These granites are stratigraphycally correlated and are considered to differ as a function of contrasts in their sources. Furthermore, the porphyritic facies of Jamon granites commonly contains plagioclase-mantled K-feldspar megacrysts. For these reasons, we prefer to consider the Jamon granites as a distinct member of the rapakivi assemblage, but this point needs further discussion.

Experimental data indicate that the characteristics of A-type granites are strongly dependent on fO_2 conditions and water content in magma sources. Besides pressure, these parameters, which are related to the nature of magma sources, should also be considered to explain the contrasts between different A-type granites. Oxidized A-type granites are considered to crystallize from magmas with appreciable water contents (≥ 4 wt.%). Such conditions favor the presence of clinopyroxene as a important residual phase during dehydration melting (Dall'Agnol et al., 1999c) and can explain the less typical A-type

geochemical signature of oxidized A-type granites (see Anderson and Morrison, 2005).

An Archean, sanukitoid biotite–hornblende quartz diorite source was proposed for the oxidized Jamon magmas (Dall'Agnol et al., 1999b,c) and lower crustal calc-alkaline plutons for Laurentia magnetite-series granites (Anderson and Bender, 1989; Anderson and Morrison, 2005). In general, oxidized A-type granites probably derived from oxidized lower crustal quartz-feldspathic igneous sources. Reduced A-type granites could be derived from quartz-feldspathic igneous sources, with a reduced character (Anderson and Morrison, 2005) or, possibly, with a metasedimentary rock contribution (Dall'Agnol et al., 2005), or, alternatively, from differentiated tholeiitic sources (Frost and Frost, 1997; Frost et al., 1999). The imprint of these different magma sources is largely responsible for the geochemical and petrological contrasts between distinct A-type granite groups.

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